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14. ABSTRACT
Picosecond time-resolved laser-induced fluorescence (PITLIF) has been shown to be a valuable tool for turbulent combustion research. The laser system enhancement enabled by this grant has significantly increased the range of systems that may be studied utilizing the PITLIF method. The enhance laser system has increased the frequency tripled laser power by nearly an order of magnitude from 35 mW for the previous system to over 300 mW for the current system (at 306.5 nm). Additionally, pump laser noise has been decreased by over -40 dB in a similar comparison. The enhanced system has allowed a range of combustion systems of interest to the Air Force to be studied including thermoacoustic instabilities and partially premixed turbulent combustion.

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Laser diagnostics, turbulent combustion, thermoacoustic instabilities, partially premixed combustion

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ENHANCED LASER SYSTEM FOR TWO-POINT SCALAR TIME-SERIES MEASUREMENTS IN TURBULENT PARTIALLY PREMIXED FLAMES

AFOSR Grant Number FA9550-06-1-0350
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SUMMARY/OVERVIEW

Previous and current work for AFOSR has demonstrated the feasibility and applicability of picosecond time-resolved laser-induced fluorescence (PITLIF) for on-the-fly, quenching-corrected measurements of minor-species concentrations in turbulent flames. Specifically, quantitative time series for OH and CH concentrations on a time scale shorter than that characteristic of turbulence have been demonstrated. Such time series can be analyzed to determine autocorrelation functions, power spectral densities (PSDs) and integral time scales. During the last three years, single-point PITLIF measurements in turbulent non-premixed and partially premixed flames have shown that normalized power spectral densities are well approximated by large eddy simulations (LES) when using a one-dimensional laminar flamelet model. In addition, PITLIF has been extended to two-point measurements, thus expanding the capabilities of the measurement method beyond temporal towards spatial statistics, including specifically the integral length scale. The application, for the first time, of two-point PITLIF to $CH_4/H_2/N_2$-air partially premixed flames with the goal of understanding their implementation in turbulent jets and thrust augmentors is the subject of current AFOSR support. Hence, PITLIF is being applied to conditions that realistically simulate both gas-turbine combustors and associated augmentors. Since PITLIF is a linear fluorescence process, the method is limited by the laser power used to excite the molecules of interest. The laser system improvement facilitated in this grant consisted of an $Nd:YVO_4$ pump laser and a high efficiency harmonic generator. These changes have improved our existing PITLIF system significantly by increasing the laser power and, in turn, the signal-to-background ratio at the wavelengths of interest by 10 fold. These system changes have reduced the amplitude variation of the pump laser by over an order of magnitude, improving the signal to noise ratio and allowing even higher bandwidth. These changes allow measurements that were only marginal or could not be practically made to be

achieved with the current improved system. Many of these measurements are of greater interest to the Air Force. This system is being used to exploit the unique capability of PITLIF with respect to determination of PSDs, autocorrelation functions, integral time scales, and integral length scales to provide a new pathway for understanding turbulence-chemistry interactions, especially in turbulent partially premixed flames with specific applications to both laboratory-scale and practical devices, including thrust augmentors. Two examples of current AFOSR-supported research made possible by this grant are presented in the next section. The examples include two-point time-series measurements of OH in four turbulent partially premixed H_2CH_4 – air flames and preliminary studies of thermoacoustic instabilities in a Rijke combustor.

TECHNICAL DISCUSSION

Two-point time-series measurements of OH have been obtained in four turbulent partially premixed H_2/CH_4 - air flames by employing the recently developed two-point picosecond time-resolved laser-induced fluorescence (PITLIF) technique. Spatial and temporal autocorrelation functions and corresponding integral length and time scales, were computed from the time series, permitting a detailed investigation of OH concentration [OH] structures within the partially premixed flames. By varying the Reynolds number and fuel-stream equivalence ratio, the effects of these parameters on the integral length and time scales were examined. Interpretation of these results relies on knowledge of turbulent nonpremixed jet flames and premixed combustion, which highlights turbulence-chemistry interactions.

Taking advantage of the high-speed measurement capacity of PITLIF, thermoacoustic instabilities also were investigated in a Rijke combustor. Simultaneous pressure and OH concentration time series were obtained in preliminary studies of a premixed CH_4 – air flame supported on a flat honeycomb ceramic flameholder in a closed-open tube configuration. These time series were analyzed using statistical and spectral techniques similar to those utilized for the turbulent partially premixed flames, as well as for singular spectrum analysis (SSA). Capable of analyzing both stationary and non-stationary phenomena, SSA provides an additional tool for studying thermoacoustic instabilities in combustors.

1. Partially Premixed Flames

Turbulent partially premixed flames (PPFs) are an important mode of combustion owing to their pervasiveness in practical combustion systems, including most gas-fired furnaces, gas-turbine engines, direct-injection engines, and even nonpremixed combustion systems with local extinction and reignition. Unlike nonpremixed and premixed flames, which typically contain a single reaction zone and can be described conveniently by a single conserved scalar, PPFs display complex flame structures often involving double- or even triple-flames,[1-2] hence giving rise to great difficulties in modeling PPFs. Quantitative experiments thus are valuable to elucidate flame structures and to validate combustion models.

Multi-point high-speed measurements provide important perspectives to understand turbulent combustion. In particular, two-point time-series measurements of important scalars, such as temperature[3] and mixture fraction[4], which have been demonstrated with high repetition-rate, laser-based techniques, reveal temporal, as well as spatial, statistics and shed light on the structures and dynamics of scalars within flames. By implementing two-point PITLIF[5-6], two-point time series of minor species concentrations, such as [OH], can be obtained to study interactions between hydrodynamic mixing and combustion chemistry, as has been demonstrated successfully in a set of turbulent nonpremixed jet flames[6-7]. In the present study, a recently developed two-point PITLIF technique is applied to a series of turbulent partially premixed H_2/CH_4-air jet flames, with different fuel-stream equivalence ratio (Φ) and Reynolds number (Re).

As shown in Figure 1, distinct double [OH] peaks can be found for a partially premixed flame with equivalence ratio $\Phi = 1.2$, where the inner peak is the rich premixed flame front and the outer peak the nonpremixed front. With increasing Φ, the two flame fronts start to merge and eventually disappear for $\Phi = 2.0$. An increase in Reynolds number also causes the two flame fronts to merge. At the same down stream distance measured relative to the burner jet diameter (z/D), the nonpremixed peak has a higher OH concentration than the premixed peak, as the OH radical is produced mainly through oxidation reactions within the nonpremixed front. Peak [OH] values decrease with increasing downstream distance, which can be attributed to the enhanced

[1] Z. Shu, C. W. Choi, S. K. Aggarwal, V. R. Katta, and I. K. Puri, *Combustion and Flame* 118 (1999) 91–107.
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[3] C. Ghenai and I. Gokalp, *Experiments in Fluids* 24 (1998) 347-353.
[4] M. E. Kounalakis, Y. R. Sivathanu, and G. M. Faeth, Journal of Heat Transfer 113 (1991) 437-445. (1991).
[5] J. Zhang, K. K. Venkatesan, G. B. King, N. M. Laurendeau, and M. W. Renfro, *Optical Letters* 30 (2005), 3144-3146.
[6] J. Zhang, G. B. King, N. M. Laurendeau, and M. W. Renfro, Two-point time-series measurements of hydroxyl concentration in a turbulent nonpremixed flame. *Applied Optics*, accepted for publication (Apr. 2007).
[7] J. Zhang, G. B. King, N. M. Laurendeau, and M. W. Renfro, Two-point OH time-series measurements in non-premixed turbulent jet flames, Proceedings of the 2006 Technical Meetings of the Central States Section, The Combustion Institute, Cleveland, OH, 2006.

residence time for slow three-body recombination reactions. The full width at half maximums (FWHM)s of the [OH] profiles also increase with height, indicating a thickened OH zone and greater flame corrugation.

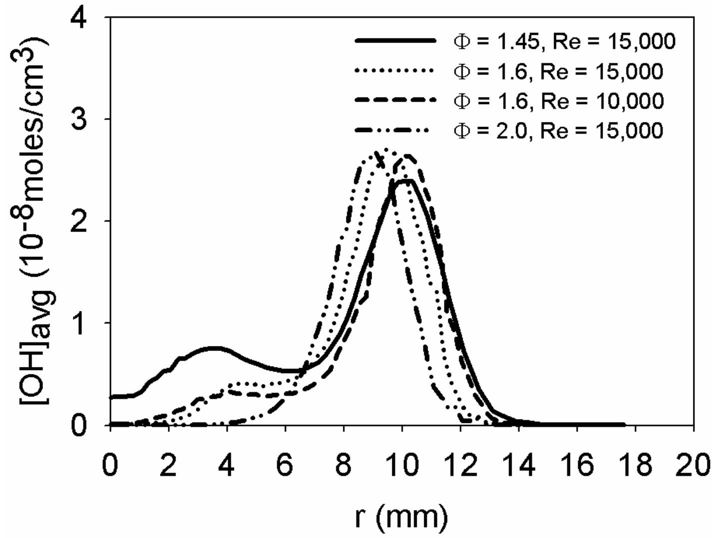
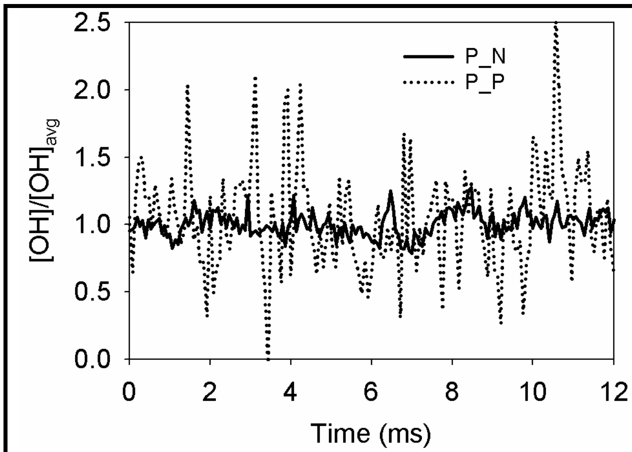


Fig. 1. Radial profiles of time-averaged [OH] for the four flames at z/D = 10.

Figure 2 shows typical time-series data measured at the mean nonpremixed and premixed peaks for the Φ = 1.45 case at Re = 15000. Compared with the nonpremixed peak, the rich premixed peak features rapid [OH] fluctuations with greater amplitude and intermittency. The corresponding temporal autocorrelation function, as shown in Fig. 3, displays a steeper decay at the mean premixed peak. This distinction between two flame locations can be explained by differences in flame structure.



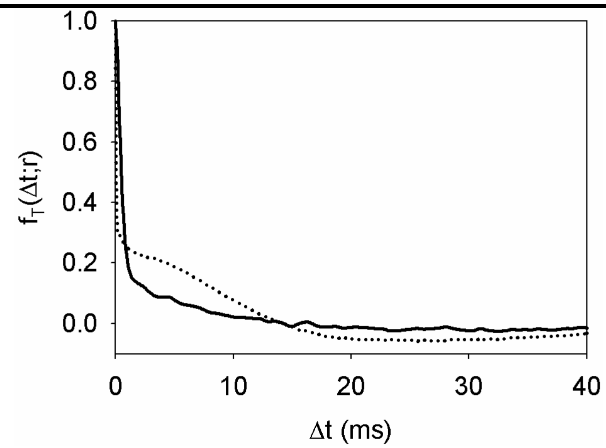


Fig. 2. Representative time series of [OH] at the mean nonpremixed peak (P_N) and the mean premixed peak (P_P) within the flame at Φ = 1.45 and Re = 15000 for z/D=10.

Fig. 3. Hydroxyl temporal autocorrelation functions at the mean nonpremixed peak (P_N) and mean premixed peak (P_P) for the flame at Φ = 1.45 and Re = 15000 for z/D=10.

The rich premixed front is located within the mixing layer lower in the flame and thus is affected strongly by jet turbulence. In contrast, the nonpremixed front lies close to (or even outside) the edge of the turbulent mixing layer which, together with residual laminarization, leads to relatively slow fluctuations in [OH]. Moreover, the premixed front can propagate and is thus more susceptible to flow-field variations. Both factors contribute to rapid [OH] fluctuations at the mean premixed peak.

Spatial autocorrelation functions for the flame with Φ = 1.45 and Re = 15000 are shown at the nonpremixed peak in Fig. 4a. In general, the spatial autocorrelation functions broaden with downstream distance, indicating an increased coherence length, which is similar to that in nonpremixed jet flames and thus similarly can be attributed to a growth in the mixing layer and to thickened OH structures. The spatial autocorrelation functions are typically not symmetric with respect to displacement Δr along the fuel and air sides, a behavior probably due to the proximity of the measurement location to the jet axis and the presence of an additional flame front. At z/D=10, the spatial autocorrelation function exhibits a negative value at large displacements instead of an exponential approach towards zero, as found in most turbulent nonpremixed jet flames.

This behavior may suggest the presence of large-scale coherent structures, i.e., vortices. Figure 4b displays corresponding spatial autocorrelation functions at rich premixed peaks. Compared

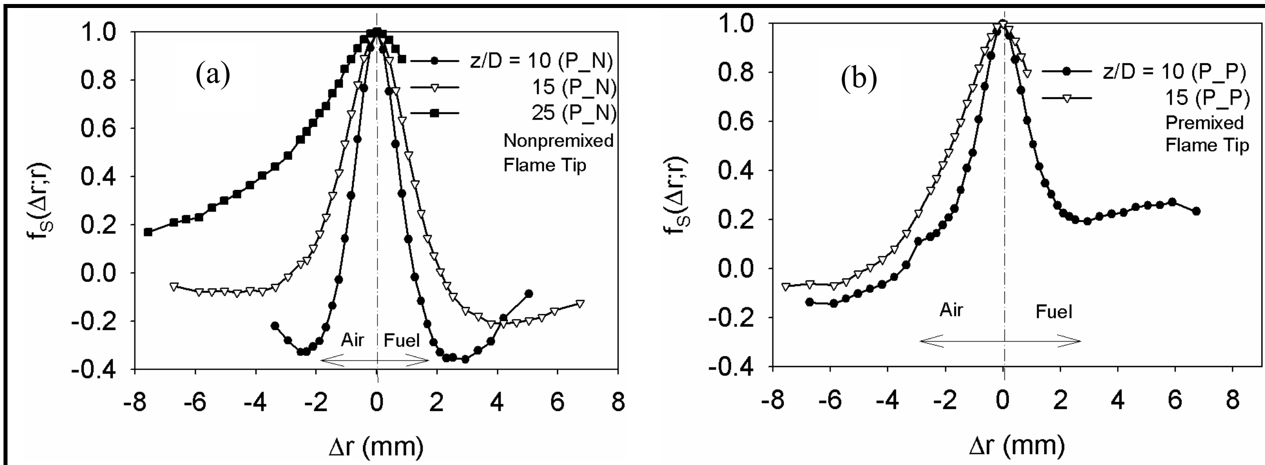


Fig. 4. Measured spatial autocorrelation functions for the flame with Φ = 1.45 and Re = 15000 at the (a) mean nonpremixed peak (P_N) and (b) mean premixed peak (P_P).

with those at the nonpremixed peak, the spatial autocorrelation functions at the premixed peak are typically broader. Moreover, in the near-nozzle region (z/D=10), the spatial autocorrelation function displays much greater asymmetry between the fuel-side and air-side displacements, which can be explained by the fact that this location is even closer to the jet axis.

2. Rijke Combustor

Thermoacoustic instabilities (TAIs) always have been an obstacle in the design and operation of solid and liquid rockets[8], as well as of gas turbines and thrust augmentors[9]. In the present section, the application of PITLIF to the study of thermoacoustic instabilities is discussed for an optically accessible Rijke tube combustor. A Rijke combustor is perhaps the simplest configuration capable of self-excited TAIs. Operating points for the combustor over a range of flowrates and equivalence ratios have been determined, and preliminary time series have been obtained of both pressure and relative [OH]. Additionally, the use of an alternative analytical technique is explored applicable to non-stationary time series.

The Rijke combustor consists of a stainless steel tube of dimensions 9.0×9.0×91.4 cm, with the height extendable to 152 cm. Fused quartz windows permit optical access for laser-based measurements. The tube operates in an acoustically closed-open configuration, with premixed CH_4-air entering the bottom through a sintered metal plate. The flameholder is a 62 cell/cm^2 cordierite honeycomb with variable axial position. When the flameholder is at the tube midpoint the second standing wave mode is excited in fulfillment of the Rayleigh criterion[10]. The result is a transient increase in sound pressure, followed by a steady-state limit cycle.

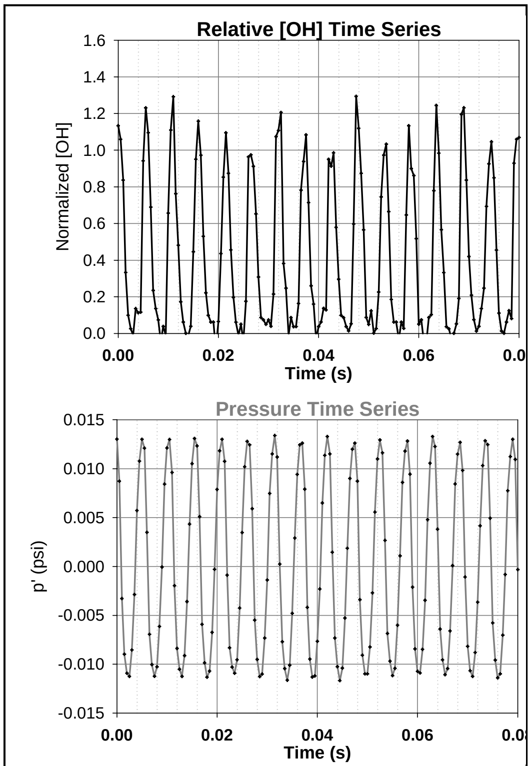


Figure 5, Relative [OH] and pressure time series for z = 0.5 mm, ϕ = 0.7, Q = 30 slpm.

The limit cycle [OH] oscillations are shown in Fig. 5, along with an associated pressure time series. Corresponding power spectra show peaks at the second mode of the tube (189 Hz), as well as harmonics of this frequency. For Fig 5, z is the height above the flameholder, Φ is the equivalence ratio, and Q is the total flow rate. In addition to Fourier analyses, these data were examined using singular spectrum analysis (SSA)[11], a procedure designed to extract information

[8] A.A. Putnam, W. R. Dennis, Journal of the Acoustical Society of America 28 (1956) 246
[9] S. Sivasegaram, J.H. Whitelaw, AIAA/SAE/ASME/ASEE 23rd Joint Propulsion Conference (1987) AIAA-87-2107
[10] L. Nord, A Thermoacoustic Characterization of a Rijke-type Combustor (2000), PhD Thesis, Virginia Tech
[11] M. Ghil et al, Reviews of Geophyics 40 (2002) 3.1-3.41

from short, noisy and/or non-stationary time series. SSA is thus capable of providing new insight into the physics unresolved by Fourier analyses.

The starting point of SSA is to embed the time series ($P(t)$: t = 1, …, N) in a vector space of dimension M, essentially representing the time series as a trajectory in phase space of the hypothetical system that generated the time series. In more general terms, this approach creates a succession of overlapping 'views' of the series through a sliding M-point window which is used to create a covariance matrix. Linear algebraic techniques then can be applied to this matrix to produce a noise-reduced reconstruction of the original time series. SSA mainly has been used for data adaptive signal-to-noise (S/N) enhancement and for recognizing patterns in noisy time series. An important feature of SSA is that the patterns need not be linear, and embedded oscillations can be amplitude-modulated and phase-modulated. Furthermore, unlike spectral methods, SSA does not require the signal to be statistically stationary and thus may be applied to non-limit cycle instabilities.

Scientific Equipment Purchased

The follow table summarizes the equipment purchased with this grant. All equipment was acquired from Spectra-Physics, P. O. Box 7013, Mountain View, California, 94039-7013. The contact and Field Sales Engineer was Mr. Art Camire, phone number (630) 904-2309.

Item	Description	Total
1.	Millennia PRO 10 sJ Ultra-compact high power, Diode Pumped Solid State laser.	$98,000.
2.	NP-MILL 10 Upgrade Millennia to 15 Watt output power	$17,000.
3.	GWU-23PL 2nd, 3rd and 4th harmonic generator for ps. operation (fundamental range 840-1000 nm).	$34,000.
4.	GWU-2WSL Wavelength selector for 1st and 2nd harmonics.	$950.
5.	SB-TSUN Extended broadband optics, upgrade to Tsunami for high power Millennia pumping	$18,000.
	Total	$167,950

Conclusion

The laser system improvement facilitated by this DURIP grant has allowed greater measurement capabilities than were afforded by our previous system. Furthermore, this new system has allowed for the development of multi-beam PITLIF excitation arrangements that enable stream-wise two-point measurements owing to the 10 fold increase in laser power at the wavelength of interest. More realistic combustion environments now may be studied because of the improved signal to noise ratio of the new laser system.